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How to Search for Pentaquarks in High Energy Hadronic Interactions

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Abstract

The strange-anticharmed Pentaquark is a $uud\bar{c}s$ or $udd\bar{c}s$ five-quark baryon that is expected to be either a narrow resonance, or possibly even stable against strong and electromagnetic decay. We describe this hyperon here, its structure, binding energy and lifetime, resonance width, production mechanisms, production cross sections, and decay modes. We describe techniques to reduce backgrounds in search experiments and to optimize the conditions for Pentaquark observation. Possibilities for enhancing the signal over background in Pentaquark searches are investigated by examining predictions for detailed momentum and angular distributions in multiparticle final states. General model-independent predictions are presented as well as those from two models: a loosely bound $D_s^- N$ molecule and a strongly-bound five-quark system. Fermilab E791 data, currently being analyzed, may have marginal statistics for showing definitive signals. Future experiments in the spirit of the recent CHARM2000 workshop, such as FNAL E781 and CERN CHEOPS with $10^6 - 10^7$ reconstructed charmed baryon events, should have sensitivity to determine whether or not the Pentaquark exists.

1. Introduction

Ordinary hadrons are mesons or baryons, whose quantum numbers can be described by quark-antiquark or three-quark configurations. Unusual hadrons that do not fit this picture would constitute new forms of hadronic matter - exotic hadrons. Such hadrons may have valence multiquark configurations such as $qq\bar{q}\bar{q}$ and $qqqq\bar{q}$. Exotic hadrons can have anomalous quantum numbers not accessible to three-quark or quark-antiquark structures (open exotic states) or even usual quantum numbers (cryptoexotic states). Cryptoexotic hadrons can be identified only by their unusual dynamical properties (anomalously narrow decay widths, anomalous branching ratios, etc.). The discovery of exotic hadrons would have far-reaching consequences for quantum chromodynamics, for the concept of confinement, and for specific models of hadron structure (lattice, string and bag models). Detailed discussions of exotic hadron physics can be found in recent reviews [1, 2, 3, 4, 5].

We consider here possible exotic hadronic states which contain quarks with four different flavors. The states have quark configurations $Qq\bar{q}\bar{q}$ and $qqqq\bar{Q}$, with one heavy quark $Q(c,b)$ and also lighter quarks $q(u,d,s)$. Their properties follow from the general hypothesis of “flavor antisymmetry” [6], by which quark systems characterized by the maximum possible antisymmetry of quark flavors (both quarks and antiquarks) are the most strongly bound. For instance, this means that the $u\bar{u}d\bar{s}$ system with ordinary $d\bar{s}$ flavors would be more bound than the $u\bar{u}d\bar{s}$ one with exotic values of charge $Q_c = +2$, etc. Jaffe [7] predicted in this spirit that for dibaryons with six light quarks, the most bound is the Hexaquark $H = [uuddss]$ combination, for which not more than two quarks are in states with identical flavors.

Thus, for the mesons and baryons with three types of light quark constituents (u,d,s), the “flavor antisymmetry” principle predicts that the states with open exotic charges and flavors are not so strongly bound and may have decay widths too large to be really observable. This may explain why the main candidates for light quark exotics have cryptoexotic characteristics or are states with exotic J^{PC} values, rather than having open exotic flavors such as mesons with $Q_c = \pm 2$, or $S = \pm 2$, baryons with $S > 0$, or $Q_c > 2$ and so on.

The situation can change for the exotic hadrons with four different quark constituents u, d, s, c or u, d, s, b , etc. For these states the flavor antisymmetry principle allows the existence of strongly bound states with open exotic

charges and flavors. Thus, Lipkin [8] and Gignoux *et al.* [9] showed that 5-quark “anticharmed” baryons (Pentaquarks) of the $P^0 = [uud\bar{c}s]$ and $P^- = [udd\bar{c}s]$ type, or analogous “anti-beauty” baryons, are the most bound in the 5-quark sector. There are also predictions [6, 10] for the most bound tetraquark exotic meson, the $\tilde{F}_s = [cs\bar{u}\bar{d}]$. The present report focusses on such exotic states, with one heavy quark. At the CHARM2000 workshop [11], a shorter version of the present work was presented [12]. The properties of exotic pentaquark baryons $[qqqq\bar{q}, sqqq\bar{q}, ssqq\bar{q}, sssq\bar{q}, ssss\bar{q}, qqqs\bar{s}, qqss\bar{s}]$ have been also discussed by Kaidalov, Grigoryan, Ferrer, Strakovsky, and others [13, 14, 15] (see also [1] and references therein).

2. Pentaquark Binding Energy

A very interesting situation can be realized, if there are exotic hadrons with heavy quarks, which are the bound states of known (quasi)stable particles, with masses which are below the threshold for strong decay. For example, if the Pentaquark is a bound state (ND_s^-) with the mass $M(P) < M(D_s^-) + M(N)$, such a state would decay only via weak interactions and would be quasistable. On the other hand, a resonance (ND_s^-)-state with a mass above the strong threshold, would be a short-lived state that decays strongly as $P \rightarrow N + D_s^-$.

The binding potential of a system is given by the difference between the Color Hyperfine (CH) interaction in the system and in the lightest color-singlet combination of quarks into which it can be decomposed. The wave function of the H may be written as:

$$\Psi_H = \alpha_1 \Psi_{6q} + \beta_1 \Psi_{(\Lambda\Lambda)} + \gamma_1 \Psi_{(\Sigma^-\Sigma^+)} + \delta_1 \Psi_{(\Xi^-p)}. \quad (1)$$

The lightest color singlet combination is the $\Lambda\Lambda$ system at 2231 MeV. The CH contribution to the binding energy of the H is about 150 MeV [7] in simple models of the CH interaction. Similarly, the P^0 and P^- wave functions can be written as:

$$\Psi_{P^0} = \alpha_2 \Psi_{5q} + \beta_2 \Psi_{(D_s^-p)} + \gamma_2 \Psi_{(\Sigma^+D^-)} + \delta_2 \Psi_{(\Lambda\bar{D}^0)}, \quad (2)$$

$$\Psi_{P^-} = \alpha_3 \Psi_{5q} + \beta_3 \Psi_{(D_s^-n)} + \gamma_3 \Psi_{(\Sigma^-D^0)} + \delta_3 \Psi_{(\Lambda D^-)}. \quad (3)$$

Here, the lightest color singlet is the D_s^-N system at 2907 MeV. The CH contribution to the mass splitting $M(D_s^-p) - M(P^0)$ is the same as for the H

particle, again in simple models of the color hyperfine interaction [8, 9]. The anti-Pentaquark is defined similarly. In general, whatever can be said about the Pentaquark holds true also for the charge-conjugate particles.

The calculations of Ref. [16] account for the $SU(3)_F$ breaking. It was shown that as the symmetry breaking increases, the P always retains a larger binding potential than the H, and that the binding can be several tens of MeV. The total binding energy includes the internal kinetic energy. Because the c quark is massive, the kinetic energy in the P is smaller than in the H by about 15 MeV. This improves the prospects of the P to be bound.

More recently, Takeuchi, Nussinov and Kubodera [17] studied the effects on the Pentaquark and Hexaquark systems of instanton induced repulsive interactions for three quarks in flavor antisymmetric states. They claim in this framework that both Pentaquark and Hexaquark are not likely to be bound. Also, Zouzou and Richard [10] reconsidered previous bag model calculations for the tetraquark and pentaquark. Their new calculation has weaker chromomagnetic attractions at short distances and a larger bag radius for multi-quark states compared to ordinary hadrons. They find that the Pentaquark is unbound by 80 MeV, while the \tilde{F} tetraquark is unbound by 230 MeV. Similar conclusions for the P and H were given by Fleck *et al.* [16]. Riska and Scoccola [18] recently described the Pentaquark in a soliton model, using different parameter sets. One set gives a bound state, while another gives a near threshold resonance. Chow [19] discusses the $qqq\bar{c}s$ Pentaquark in the framework of the binding of a heavy meson to a chiral soliton. Riska and Scoccola [18] and Oh et al. [20] discuss the properties of a heavy $qqqq\bar{c}$ Pentaquark without strangeness. Shmatikov [21] discusses bound pentaquarks with a molecular type baryon-meson structure, including ND^* and NB^* .

A very weakly bound D_s^-p deuteron-size bound state just below threshold with a structure very different from that of the strongly bound proton size Pentaquark might still be consistent with these recent calculations, considering all the model uncertainties. The D_s^-p system does not have Pauli blocking and repulsive quark exchange interactions which arise in all hadron-hadron systems where quarks of the same flavor appear in both hadrons. Thus, even a comparatively weak short range interaction could produce a relatively large size bound state analogous to the deuteron, with a long D_s^-p tail in its wave function and a good coupling to the D_s^-p system. Because in the Pentaquark, unlike the deuteron, there is no short range repulsion, its structure at short distances will be quite different from that of the deuteron.

This component too has its influence on the production mechanism, as discussed in subsection 4.2. The deuteron-like state will be stable against strong and electromagnetic decays. Since the D_s^-p pair has some 50-75 MeV lower mass than other meson-baryon cluster components in the Pentaquark, it will be the dominant component in a weakly bound deuteron-like Pentaquark. Considering all the uncertainties in knowing the Pentaquark binding energy, our experimental approach is to search for both strongly and weakly bound Pentaquarks, as well as unbound Pentaquark resonances.

3. Pentaquark Structure and Decay Modes

There are different possibilities for the internal structure of observable (not very broad) exotic hadrons. They can be bound states or near threshold resonance structures of known color singlet sub-systems (e.g. $\Lambda\Lambda$ for the H [22] or D_s^-p for the P^0). But they can have more complicated internal color structure, such as baryons with color octet and sextet bonds $[(qqq)_{\bar{8}_c} \times (q\bar{q})_{8_c}]$ and $[(qq\bar{q})_{\bar{6}_c} \times (qq)_{6_c}]$ (see ref. [23]). We designate all such structures as direct five quark configurations. If color substructures are separated in space by centrifugal barriers, then exotic hadron resonances can have not very broad or even anomalously narrow decay widths, because of complicated quark rearrangements in the decay processes. If these exotic hadrons are bound strongly, they can be quasistable, with only weak decays.

The wave function of the Pentaquark may contain two-particle cluster components, each corresponding to a pair of known color singlet particles; and also a direct five quark component. The Pentaquark production mechanism and its decay modes depend on these components. The P^0 can be formed for example by the coalescence of $pD_s^-, \Lambda\bar{D}^0, pD_s^{*-}, \Sigma^+D^- + \Sigma^0\bar{D}^0, \Lambda\bar{D}^{*0}, \Sigma^+D^{*-} + \Sigma^0\bar{D}^{*0}$; or by a one-step hadronization process. Let us consider three color-singlet components of the P^0 : D_s^-p (2907 MeV), $D^-\Sigma^+$ (3058 MeV) and $\bar{D}^0\Lambda$ (2981 MeV). The relative strengths of these components depend strongly on the binding energy, as discussed above for the deuteron-like Pentaquark. Pentaquark searches in progress in E791 [24, 25] are based on the charged particle decay components of different Pentaquark decay modes: $D_s^-p \rightarrow \phi\pi^-p$ (B=3.5%), $D_s^-p \rightarrow K^{*0}K^-p$ (B=3.3%), $D^-\Lambda \rightarrow K^+\pi^-\pi^-\Lambda$ (B=8%), $\bar{D}^0\Lambda \rightarrow K^-\pi^+\Lambda$ (B=4%) and $\bar{D}^0\Lambda \rightarrow K^-\pi^+\pi^+\pi^-\Lambda$ (B=8%). The indicated branching ratios are those

of the on-shell D-meson. Such Pentaquark branching ratios are plausible in a model where the D meson decays weakly, while the proton and Λ act as spectators. Weak decays of virtual color singlet substructures in bound states are possible, ΛD^0 or $\Sigma^+ D^-$ for example, if their masses are smaller than the $D_s^- p$ threshold. In other cases, there would be strong decays through quark rearrangement $(\Sigma^+ D^-)_{bound} \rightarrow D_s^- + p$, and so on. Even if the masses are smaller, the phase space favors decay to the lightest system. The phase space factor would cause the partial width for any decay mode to be smaller than for the on-shell decay, making the total lifetime longer.

The decay through the direct five-quark component may open many additional channels, which may shorten the lifetime of the Pentaquark and reduce the experimental possibilities to observe it. The direct five-quark P^0 component may for example decay weakly via Cabibbo allowed or suppressed direct or exchange diagrams. As a result, the P^0 may decay into $\pi^- p$, $K^- p$, $\Sigma^- K^+$, $\Sigma^+ K^-$, $\Sigma^+ \pi^-$, $\Sigma^- \pi^+$, etc. Each of these decays may have one or more $\pi^+ \pi^-$ pairs, in addition to the particles shown. The observation of such decay channels would give important information on the Pentaquark internal structure. These decays may be observed, if the branching ratios are not too small. Depending on the decay mechanisms, the Pentaquark lifetime may then be shorter or longer than the D_s 467 fs lifetime. Experimental searches must therefore cover a range of possible lifetimes.

We consider two possible scenarios for the decay of Pentaquark baryons. In the first, Pentaquarks are quasistable hadrons which can decay only via weak interaction, with lifetimes of the same order as other charmed hadrons. Possible decay modes of Pentaquarks in this scenario are $P^0 \rightarrow \phi p \pi^-$, $\Lambda K^+ \pi^-$; $P^- \rightarrow p \phi \pi^- \pi^-$, $\Lambda K^+ \pi^- \pi^-$, $\Sigma^- K^+ \pi^-$; as well as those described in the previous paragraph. Such decays can be directly observed in precision vertex detectors, which are now standard devices in experiments with charmed or beauty particles. The use of vertex detectors greatly reduces the combinatorial background in the corresponding effective mass spectra, and makes it possible to search for exotic P baryon production in a wide range of the X_f observable. Searches for the tetraquark \tilde{F}_s ($cs\bar{u}\bar{d}$) could also look for weak decays [8, 26], such as $\tilde{F}_s \rightarrow K^- K^+ \pi^- \pi^+$.

In the second scenario, the Pentaquark baryons have large enough masses and are resonant states, which strongly decay with emission of secondary charmed particles (for example, $P^0 \rightarrow p D_s^-$). The search for such strongly decaying exotic hadrons must also use vertex detectors for detection of

the D_s^- . For the identification of Pentaquarks, only the study of effective mass spectra of secondary decay products can be used, for which there is a large combinatorial background. It is well known [1, 26] that the combinatorial background is significantly reduced in the fragmentation region (at $X_f > 0.5 - 0.6$), and such kinematics is therefore strongly desirable for the resonance Pentaquark searches. This experimental task is more challenging and is crucially dependent on the Pentaquark decay width. Only narrow states with $\Gamma \leq 100$ MeV have a good chance to be separated from the background. Narrow states may arise for a variety of reasons not necessarily related to exotic properties, as when the phase space for decay is small. For example, the $\Lambda(1405)$ is 80 MeV above the $\Sigma\pi$ threshold and has a width of 50 MeV. The $D^*(2010)$ and the $\Lambda_c^*(2625)$ are about 40 MeV above their respective thresholds and their widths are less than 2 MeV. Another important possibility is a narrow width that may arise from the complicated internal color structure of an exotic hadron, and by a quark rearrangement mechanism in the decay processes for multiquark exotic object, leading to a colorless final state [23, 26, 27]. Another possible cause for a narrow state may be the reduced effective phase space as a result of OZI suppression of some decays for an exotic state with hidden strangeness or charm [1], as will be discussed in Section 5.

4. Experimental Pentaquark Search

An experimental program to search for the Pentaquark should include:

- (1) Reactions likely to produce the Pentaquark, complemented by an estimate of the production cross section.
- (2) Experimental signatures that allow identification of the Pentaquark.
- (3) Experiments in which the backgrounds are minimized.

These points will be further discussed in the following subsections.

4.1 Experimental Considerations

All charm experiments require vertex detectors consisting of many planes of silicon micro-strips with thousands of channels. Fermilab E791 [24, 25, 28] used 23 such planes. Some of the planes are upstream of the target for beam tracking. These detectors allow a high efficiency and high resolution for

reconstruction of both primary (production) vertex and secondary (decay) vertex. The position resolution of the vertex detectors is typically better than 300 microns in the beam direction. By measuring the yield of a particle as a function of the separation between the two vertices, the lifetime of the particle is obtained. This is possible as long as the lifetime is not so short, such that the separation of vertices becomes ambiguous. Other major components in charm experiments are several magnetic spectrometers with track detectors for track reconstruction and for momentum analysis, Cherenkov counters for particle identification, and electromagnetic and hadronic calorimeters. Muon detectors and TRD detectors for electron separation are included for studies of leptonic decays. The invariant mass resolution for typical charm masses in such spectrometers is about 10 MeV. Different spectrometers are sensitive to different regions of Feynman X_f values.

In hadronic production, the charm states produced are preponderantly charm mesons at low X_f . The triggers for such experiments vary. In E791, the requirement was to ensure an interaction in the target (using signals from various scintillators) and a transverse energy (E_t) larger than some threshold [24, 25, 28]. The rest of the charm selection was done off-line. Future experiments are planned to obtain higher yields of charmed hadrons. Increased charm sensitivity can be achieved as in E781 [29] by using higher integrated beam intensities, and higher efficiency detector systems. E781 also will use a trigger condition that identifies a secondary vertex, and also requires positive particles with momentum greater than 15 GeV/c. This should enhance the high- X_f acceptance ($X_f > 0.1$), and give higher quality events. A good charm trigger [29] can produce an enriched sample of such high X_f charm baryons with improved reconstruction probability because of kinematic focusing and lessened multiple scattering with a significantly lower number of events written to tape or disk. CHARM2000 experiments will also require charm enhancement triggers [30]. The present E791 [28] and future E781 [29] and CHARM2000 experiments [31, 32, 33] complement each other in their emphasis on different X_f regions, incident particle types, statistics and time schedules.

High quality particle identification (PID) for the largest possible energy range of the outgoing particles is important for reducing backgrounds associated with incorrect identification of tracks. In E791, two threshold Cerenkov detectors were used for this purpose. In E781, this will be available via ring imaging Cerenkov (RICH) and transition radiation detector (TRD) PID sys-

tems. These and other experimental techniques to reduce backgrounds are described in more detail in [11].

4.2 Pentaquark Production Mechanisms

We consider possible mechanisms for P formation. For the central hadron-nucleus charm production at several hundred GeV/c, the elementary process is often associated with $q\bar{q} \rightarrow c\bar{c}$ or $gg \rightarrow c\bar{c}$ transitions. The produced charmed quarks propagate and form mini-jets as they lose energy. Hadronization associated with each jet proceeds inside the nucleus, and to some extent also outside the nucleus; depending on the transverse momentum of the jet. The propagating charmed quarks may lose energy via gluon bremsstrahlung or through color tube formation in a string model, or by other mechanisms, as discussed in ref. [34] and references therein. One may form a meson, baryon, or Pentaquark, according to the probability for the charmed quarks to join together with appropriate quarks and antiquarks in the developing color field. One can estimate Pentaquark production cross sections via one-step and also two-step hadronization. All such estimates are very rough. Our aim is to account for major ingredients in estimating the cross section, and to give a conservative range of values. For one-step hadronization, the \bar{c} joins directly to the other quarks. The one-step is the usual mechanism for meson and baryon formation. For two-step, the first involves meson and baryon hadronization, while the second involves meson-baryon coalescence.

We first consider estimates for the central production cross section assuming a meson-baryon coalescence mechanism, expected to be the main mechanism for production through the long-range (deuteron-like) component of the Pentaquark wave function. We make a crude estimate relative to the D_s^- , an anticharmed-strange meson ($\bar{c}s$). The weakly bound P (deuteron type structure) can be produced for example by coalescence of a proton or a neutron with a D_s^- , analogous to the production of a deuteron by coalescence of a neutron and a proton. The data [35] give roughly 10^{-3} for the $\sigma(d)/\sigma(p)$ production ratio. This ratio can also be applied to $\sigma(P)/\sigma(D_s^-)$ production. The reason is that in both cases, the same mass (nucleon mass) is added to the reference particle (proton or D_s^-), in order to form a weakly bound deuteron-like state. This ratio is very sensitive to the pentaquark binding energy, and may be substantially different for a larger value.

We now consider the one-step hadronization of a Pentaquark, expected to

be the main mechanism for the production through the short-range component of the Pentaquark wave function. We rely here on an empirical formula which reasonably describes the production cross section of a mass M hadron in central collisions. The transverse momentum distribution at not too large p_t follows a form given as [36]:

$$d\sigma/dp_t^2 \sim \exp(-C\sqrt{M^2 + p_t^2}), \quad (4)$$

where C is roughly a universal constant $\sim 5 - 6 \text{ (GeV)}^{-1}$. The exponential (Boltzmann) dependence on the transverse energy $E_t = \sqrt{M^2 + p_t^2}$ has inspired speculation that particle production is thermal, at a temperature $C^{-1} \sim 160 \text{ MeV}$ [36]. We assume that this equation is applicable to Pentaquark production. To illustrate the universality of C , we evaluate it for a few cases. For Λ_c and Ξ^0 , empirical fits to data give $\exp(-bp_t^2)$, with $b=1.1 \text{ GeV}^{-2}$ and $b=2.0 \text{ GeV}^{-2}$, respectively [37, 38]. With $C \approx 2 \cdot b \cdot M$, this corresponds to $C \sim 5.0 \text{ GeV}^{-1}$ for Λ_c , and $C \sim 5.3 \text{ GeV}^{-1}$ for Ξ^0 . For inclusive pion production, experiment gives $\exp(-bp_t)$ with $b = 6 \text{ GeV}^{-1}$ [39]; and $C \sim b$, since the pion mass is small. Therefore, $C = 5-6 \text{ GeV}^{-1}$ is valid for Λ_c , Ξ^0 hyperon, and pion production. After integrating over p_t^2 , we estimate the ratio as:

$$\sigma(P)/\sigma(D_s^-) \sim \exp[-5[M(P) - M(D_s^-)]] \sim 10^{-2}. \quad (5)$$

In applying Eq. 5 to Pentaquark production, we assume that the suppression of cross section for the heavy P as compared to the light D_s^- is due only to the increased mass of P . The formula ignores dynamical considerations, such as the particular one-step or two-step hadronization processes, or the size of the P . It also does not account for threshold effects. Consequently, there may be large uncertainties in its application.

Both reaction mechanisms described above can contribute to the production cross section, which is estimated in the range of $\sigma(P)/\sigma(D_s^-) \sim 10^{-3} - 10^{-2}$. In actual measurements, the product $\sigma \cdot B$ for a particular decay mode is measured, where B is the branching ratio for that mode. If a Pentaquark peak is not observed, assumptions on the values of B and on the P lifetime may be necessary in order to set limits to the Pentaquark production cross section.

Another approach for the $\sigma(P)$ cross section evaluation is based on a comparison of Pentaquark and charmed-strange baryon Ξ_c^0 (csd) production

reactions. This method was previously applied in [24, 25, 26]. For example, with a high energy hyperon beam, one may compare P^0 production ($uud\bar{c}s$) to Ξ_c^0 (csd) baryon production. Processes with charm baryon production involve $c\bar{c}$ pair creation, followed by c or \bar{c} hadronization in the final states. There should therefore not be much difference for c or \bar{c} fusion, so that one may compare P^0 to Ξ_c^0 production. The production of P^0 is also different from Ξ_c^0 due to the fusion of an additional uu quark pair. This would cause a reduction factor R for the cross sections:

$$\sigma_{\Sigma}(P^0) = R\sigma_{\Sigma}(\Xi_c^0) \geq 2.5 \times 10^{-3} \sigma_{\Sigma}(\Xi_c^0). \quad (6)$$

This factor $R \geq 2.5 \times 10^{-3}$ can be estimated from the data on other processes with additional quark fusion in the particles under study. For example, the relative yields $\bar{d}/\bar{p} \simeq 10^{-4}$, ${}^3\bar{H}e/\bar{p} \simeq 10^{-8}$ [34, 35, 40] give information on the fusion probability of 3 and 6 additional quarks. It is then possible to obtain an average reduction factor $\sim 5 \times 10^{-2}$ per fusion for each additional quark, yielding the value $R > 2.5 \times 10^{-3}$ in Eq. 6. The inequality arises because antinuclei are loosely bound systems whose yields implicitly include this factor.

4.3 Pentaquark Decay Signatures

(1) Mass, Width and Decay Modes

Searches for the Pentaquark are easiest via modes having all final decay particles charged. With all charged particles detected, the invariant mass of the system can be determined with high resolution. One signature of the Pentaquark is a peak in the invariant mass spectrum somewhat lower than 2907 MeV if the system is bound; and above if it is a resonance. The position of the peak should be the same for several decay modes. It's width should be determined by the experimental resolution if it is bound, and broader if it is a resonance.

The selection of the decay modes to be studied is made primarily by considering detection efficiency and expected branching ratios. Since the $D_s^- p$ system is the lightest, it is expected to be preferred from phase space arguments. Also, two of it's decay modes have four charged particles in the final state (e.g. $\phi\pi^-p$, $\phi \rightarrow K^+K^-$; $K^{*0}K^-p$, $K^{*0} \rightarrow K^+\pi^-$). This signature was implemented in E791 [24, 25]. First, two distinct vertices were

identified, a production vertex and a decay vertex. From the decay vertex, four tracks were identified and associated with $K^+K^-\pi^-p$. By reconstructing the invariant mass of the K^+K^- pair, only ϕ mass events were accepted and the invariant mass of all four particles was reconstructed. A peak in the resulting spectrum will be one of the identifying characteristics of the Pentaquark.

(2) One General Signature - A Spectator Baryon:

We first note a striking signature for Pentaquark decay which may be useful for discrimination against background. This signature is predicted by both of two very different Pentaquark models: (1) a loosely-bound D_s^-p deuteron-like state and (2) a strongly-bound five-quark state. Both models predict decay modes into a baryon and two or more mesons, in which the three quarks in the baryon are spectators in the decay process and remain in the final state with a low momentum which is just the fermi momentum of the initial bound state.

That the baryon is a spectator is obvious in the deuteron model, in which the decay is described as an off-shell D_s^- decaying with a nucleon spectator. In the five-quark model, a similar situation arises in the commonly used spectator model with factorization. Here, the charmed antiquark decays into a strange antiquark by emission of a W^- which then creates a quark-antiquark, which hadronizes into mesons. The strange antiquark combines with one of the four spectator quarks to form one or more mesons, while the three remaining spectator quarks combine into a baryon.

In both cases, it seems that the final state should show a low-momentum baryon in the center-of-mass system of the Pentaquark and the invariant mass spectrum of the remaining mesons peaked at the high end near the kinematic limit. Thus in the particular cases of the $p\phi\pi^-$, $K^{*0}K^-p$ and $\Lambda K^+\pi^-$ decay modes, the $\phi\pi^-$, $K^{*0}K^-$ and $K^+\pi^-$ invariant mass distributions respectively should show this peaking near the kinematic limit.

Note that in the particular case of the $p\phi\pi^-$ decay mode, a low momentum proton in the center of mass system means that the π^- and ϕ are back to back with the same momentum and therefore that the pion carries off most of the available energy. Thus one might reduce background with a cut that eliminates all pions with low momentum in the center of mass.

(3) Some Model-Dependent Branching Ratio Predictions:

The $\phi\pi^-p$ decay mode is the most convenient for a search, since the ϕ signal is so striking. We now examine the lowest order predictions from the

two extreme models for the branching ratios of other modes relative to $\phi\pi^-p$.

In experiments sensitive only to charged particles the $\phi\pi^-p$ decay mode is observed in the four-prong final state $K^+K^-\pi^-p$. The $K^{*0}K^-p$ decay mode is also observable in this same four prong final state. The $K^{*0}K^-p$ decay mode arises naturally in the deuteron model, since the $K^{*0}K^-$ decay is observed for D_s^- decays with a comparable branching ratio to $\phi\pi^-$. In this model, the ratio of the two decays is predicted from observed D_s^- decay branching ratios with phase space corrections. However, the $K^{*0}K^-p$ decay mode does not occur in the five quark spectator model, where the spectator strange quark can only combine with the \bar{s} produced by the charm decay to make a ϕ or with two spectator nonstrange quarks to make a hyperon. Comparing the two decays thus tests the decay model.

The $K\pi\Lambda$ and $K^*\pi\Lambda$ decay modes arise naturally in the five quark spectator model, or in a moderately bound $D\Lambda$ Pentaquark. However, they should not be expected in a very weakly bound deuteron model with mainly a D_s^-p structure. In that case, the D_s^- decays into mesons containing one strange quark-antiquark pair and the baryon spectator has no strangeness.

(4) Angular Momentum Constraints and Angular Distributions for P Decays:

We can give a model-independent prediction. The Pentaquark has spin 1/2 and this total angular momentum is conserved in the decay. Since the production process is a strong interaction which conserves parity, the Pentaquark will not be produced with longitudinal polarization. Its polarization in the beam direction must also vanish. Therefore, the angular distribution in the center-of-mass system of the Pentaquark must be isotropic for the momentum of any final state particle in any decay mode with respect to either the incident beam direction or the direction of the total momentum of the Pentaquark. The background does not necessarily have these constraints.

We also give a model-dependent prediction. We first consider the deuteron model. The D_s^- has spin zero, and spin is preserved in the decay. Thus, in the center of mass frame of all the D_s^- decay products, the angle between the proton momentum and the momentum of any particle emitted in the D_s^- decay must have an isotropic angular distribution.

A further prediction is obtainable for the case of a vector-pseudoscalar decay mode of the D_s^- ; e.g. $\phi\pi^-$ or $K^{*0}K^-$. The vector meson must be emitted with zero helicity in the rest frame of the D_s^- . The zero helicity can be seen in the $\phi\pi$ decay by measuring the angle $\theta_{K\pi}$ between the kaon

momenta in the ϕ rest frame and the pion momentum. The prediction is to have a $\cos^2 \theta_{K\pi}$ distribution. By contrast, the five-quark model for the Pentaquark favors helicity one over helicity zero for the vector meson by just the 2:1 ratio needed to give an isotropic distribution in $\theta_{K\pi}$. Here again the background does not necessarily have these constraints.

4.4 Pentaquark Expected Yield

We proceed with count rate estimations for the expected yields of Pentaquark baryons. Given the need to search for both quasistable and resonant Pentaquark baryons in different regions of X_f , we give production cross sections for $X_f > 0$ and in the fragmentation region $X_f > 0.5$, where one expects an improved signal to background ratio. We use several production models for Pentaquarks. The different predictions of these models reflect the uncertainties in our expectations. We also assume that quasistable P^0 baryons would be reconstructed in selected visible weak (w) decay modes with a combined effective branching ratio B_w :

$$B_w = B[P^0 \rightarrow p\phi\pi^- + p\phi\pi^-\pi^+\pi^- + pK^{0*}K^-] \\ B_w = \simeq 0.05 ; \text{ based on } \phi \rightarrow K^+K^- \text{ and } K^{0*} \rightarrow K^+\pi^-. \quad (7)$$

In practice, one looks for the visible (charged-particle) decay modes, such as: $[D_s^- p] \rightarrow \phi\pi^-p \rightarrow K^+K^-\pi^-p$ (B=1.8%), $[D_s^- p] \rightarrow \phi\pi^-\pi^-\pi^+p \rightarrow K^+K^-\pi^-\pi^-\pi^+p$ (B=0.9%), and $[D_s^- p] \rightarrow K^{*0}K^-p \rightarrow \pi^-K^+K^-p$ (B=2.1%). The total branching ratio of these last three decay modes is 4.8%. Here we assume a $[D_s^- p]$ bound state model for the quasistable P pentaquark. Our estimate $B_w \simeq 0.05$ is somewhat lower than the total visible (charged particle) decay modes of a virtual D_s^- for $P^0 \rightarrow (pD_s^-)_{\text{virtual}}$ dissociation, where $B(D_s^-)(\text{visible}) \approx 0.08$ [41]. The 0.08 value includes possible non-resonant charged particle decays, such as $D_s^- \rightarrow pK^+K^-\pi^-$ or $D_s^- \rightarrow p\pi^+\pi^-\pi^-$. Our objective is a search that will have improved signal to background, by concentrating on final states having resonances, such as the narrow ϕ or the $K^*(890)$.

For strongly-decaying P baryon resonances, we assume the same production cross sections as for a quasi-stable Pentaquark. A reasonably small decay width can be obtained in principle in the model with direct five-quark configurations (color octet or sextet bonds, as described in Section 3 and

Ref. [23]). For detection of these baryons, one may hunt for the decay mode $P^0 \rightarrow pD_s^-$, assigned here a 100% branching ratio for this resonance possibility. This value is clearly an upper limit, and may be reduced by other strong decay channels. We for example do not take into account other possible totally reconstructable decay modes, such as $P^0 \rightarrow pD_s^-(\text{visible})\pi^+\pi^-$, $P^0 \rightarrow \Delta^0 D^-(\text{visible})K^+$. Thus, we estimate for strongly decaying pentaquarks, the branching ratio:

$$B_s[P^0](\text{visible}) = B_s = B[P^0 \rightarrow pD_s^-] \cdot B[D_s^-\text{visible}] \simeq 0.05. \quad (8)$$

One may also search for P^- Pentaquark strong decays $P^- \rightarrow D^-\Lambda$; $\bar{D}^0\Sigma^-$ (resonances).

Both weak and strong decay modes coming from the D_s^-p and the $\bar{D}^0\Lambda$ components of the P are currently being studied in E791, where the data were taken with a 500 GeV π^- beam. Analysis of a part of the E791 data already yielded a preliminary upper limit at 90% confidence level:

$$\frac{\sigma(P^0) \cdot B(P^0 \rightarrow \phi\pi p)}{\sigma(D_s^-) \cdot B(D_s^- \rightarrow \phi\pi)} < 2.6\%, \quad (9)$$

for quasistable Pentaquark production (not including systematic uncertainties) [42]. In the analysis, it was assumed that the Pentaquark has the same lifetime as a real D_s^- and a mass of 2.75 GeV. It was assumed that its production characteristics are the same as other charmed baryons. This limit was based on a part of the data and measured D_s^- yield. With the full data sample and more decay modes analyzed, several Pentaquarks may be observed if the cross section is in the range estimated in the previous section, or else the limit may be further lowered.

For the planned E781 and CHARM2000, when both use baryon beams, we rely on previous measurements done with similar beams. The Σ^- hyperon beam should be good tool for the search for strange-charmed(anticharmed) open exotic hadrons, such as the Pentaquark baryons P^0 and P^- , or tetraquark meson \tilde{F}_s . Hyperon beams are the purest high energy beams containing strange valence quarks. Thus, the inclusive reactions:

$$\begin{aligned} \Sigma^-(dds) + N &\rightarrow P^0(\bar{c}uuds) + X \\ &\rightarrow P^-(\bar{c}udds) + X \\ &\rightarrow \tilde{F}_s^0(cs\bar{u}\bar{d}) + X \end{aligned} \quad (10)$$

should be favorable for the production of strange-charmed hadrons at large X_f , since they benefit from strange quark sharing between primary and secondary particles.

We use different methods to estimate the expected cross sections for Pentaquark production in $\Sigma^- N$ interactions for the hyperon beam of Fermilab with momentum 650 GeV/c (E781). First, following section 4.2, we take $\sigma_{\Sigma^-}(P^0)/\sigma_{\Sigma^-}(D_s^-) \simeq 10^{-2} - 10^{-3}$. The $\sigma_{\Sigma^-}(D_s^-)$ cross section is estimated two ways. A neutron beam measurement with $E_n \simeq 600$ GeV [43] gave $\sigma_n(D_s^-) \cdot B(D_s^- \rightarrow \phi\pi^-) \simeq 0.76 \mu b/N$ for $0.05 < X_f < 0.35$. From the quark structure of Σ^- and the neutron, one may expect that $\sigma_{\Sigma}(D_s^-)$ is greater than $\sigma_n(D_s^-)$. Assuming conservatively that they are equal, and assuming also the X_f dependence $d\sigma(D_s^-)/dX_f \sim (1 - X_f)^5$ for the baryon primaries (see [37]), one obtains $\sigma_{\Sigma}(D_s^-)|_{X_f>0} \simeq 40 \mu b/N$. This is an exceptionally large value, considering that the entire hadronic (cq) production cross section is expected [44] to be near 20-30 $\mu b/N$. A more conservative estimate of this cross section is based on the assumption $\sigma_{\Sigma}(D_s^-) \simeq \sigma_p(D^-) \simeq \sigma_p(D^+)$ from the quark structure of the projectiles and produced mesons. The data of the EGS experiment for $X_f > 0$ with a $P_p = 400$ GeV/c momentum proton beam give $\sigma_p(D^-) \simeq \sigma_p(D^+) \simeq 3 \mu b/N$ [45]. Based on the energy dependence of charm production data [46], extrapolation to 650 GeV/c yields for E781 the estimate $\sigma_{\Sigma}(D_s^-)|_{X_f>0} \simeq 5 \mu b/N$. This smaller value is used for the estimate of P^0 exotic baryon yields in E781 (see Table 1). With $\sigma(P^0)/\sigma(D_s^-) \simeq 10^{-2} - 10^{-3}$, one obtains $\sigma(P^0) \approx 50 - 5 \text{ nb}/N$.

There are no direct data for the Ξ_c^0 production with baryon beams, and only very poor data for Ξ_c^+ (csu) production [47]. The recent WA89 experiment used a Σ^- hyperon beam at CERN, with momentum $P_{\Sigma^-} = 330$ GeV/c. The cross section measured was: $\sigma_{\Sigma^-}(\Lambda_c^+)|_{X_f>0.2} = (9.3 \pm 4.3 \pm 2.5) \mu b/N$, with $d\sigma_{\Sigma^-}/dX_f \sim (1 - X_f)^4$ [37]. Extrapolating to $X_f > 0$ (factor ~ 3) and to $P_{\Sigma^-} = 650$ GeV/c (factor ~ 1.5), one obtains $\sigma_{\Sigma^-}(\Lambda_c^+)|_{X_f>0} \simeq (30 \pm 14 \pm 8) \mu b/N$ for E781, where the uncertainties are only from scaling those of Ref. [37]. The value $30 \mu b/N$ again seems unreasonably large, which may be due to the extrapolation procedure or to the experimental uncertainties in $\sigma_{\Sigma^-}(\Lambda_c^+)|_{X_f>0.2}$. Thus, we use the more conservative estimate $\sigma_{\Sigma^-}(\Lambda_c^+)|_{X_f>0} \sim 5 \mu b/N$ for $P_{\Sigma^-} = 650$ GeV/c, close to the minimum value given by the error bars. From the quark composition of charmed baryons, it is reasonable to conclude that $\sigma_{\Sigma}(\Xi_c^0) \geq \sigma_{\Sigma}(\Xi_c^+)$ or $\sigma_{\Sigma}(\Lambda_c^+) \geq 5 \mu b/N$;

and to obtain from Eq. (6) the estimate:

$$\sigma_{\Sigma}(P^0)|_{X_f>0} \geq 13 \text{ nb}/N. \quad (11)$$

This value gives Pentaquark yields in E781 at about 25% of the upper values shown in Table 1.

We consider also the expected E781 efficiency for Pentaquark detection, by comparison to estimated [29] efficiencies for cqq decays. These include a tracking efficiency of 96% per track, a trigger efficiency averaged over X_f of roughly 18%, and a signal reconstruction efficiency of roughly 50%. The E781 Monte Carlo simulations [29] gave an average global efficiency of $\sim 8\%$, by considering the ~ 200 fs lifetime decay $\Lambda_c^+ \rightarrow pK^-\pi^+$, and the ~ 350 fs lifetime decay $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^-$. The charm baryons were assumed [29] to be produced with a cross section of the form $d\sigma/dX_f = (1 - X_f)^{4.2}$, an assumption which is built into the estimation of the trigger efficiency. For heavier Pentaquark production, it is likely that this distribution would shift to lower X_f (corresponding to an exponent greater than 4.2), and this would also reduce the efficiency. The value 8% is for reconstruction of the relatively strong signals from cqq charm baryon decays. The reconstruction efficiency may be lower for Pentaquark events. For the weaker Pentaquark signal, tighter analysis cuts with resulting lower efficiencies may be required in order to achieve the optimum signal to noise ratio. For lifetimes smaller than about 60 fs, which is possible for the Pentaquark, the trigger efficiency would also be significantly reduced [29]. Considering all the unknown variables, the final experimental statistics may then be significantly lower than the upper value estimated here, using the 8% global efficiency. From Table 1, one sees that for quasistable Pentaquark baryons, the maximum expected statistics in E781 is 280-2800 events. This may be adequate for their observation, if they really exist.

From $d\sigma/dX_f \sim (1 - X_f)^4$ for charmed baryons [37], we estimate the Pentaquark production cross section in the $X_f > 0.5$ fragmentation region (quasi-stable or resonant) as $\sigma_d \sim 0.03 \cdot \sigma(X_f > 0)$; as given in Table 1. The fragmentation region should be most effective for reducing the combinatorial background in both quasi-stable and resonance Pentaquark searches. In the latter case, one studies a strong decay into $D_s^- p$, if the P is a short-lived resonance with mass $M(P^0) > M(D_s^-) + M(N)$. For this strong decay, the proton and D_s^- come from primary vertex, and the D_s^- decay forms

the secondary vertex. The expected maximum numbers of events in the fragmentation region is quite limited (from 28 to 280 events, from Table 1), and there are moderate chances for P^0 observation as a peak in the mass spectrum of $M(pD_s^-)$.

It is possible that different mechanisms for charm production contribute in different X_f regions. For example, there is evidence for leading production of charmed hadrons in WA89 and FNAL E769 [48] and E791 [49]. One can also consider a diffractive mechanism for Pentaquark production. Brodsky and Vogt [50, 51] suggested that there may be significant intrinsic charm (IC) $c\bar{c}$ components in hadron wave functions. The Hoffmann and Moore analysis [52] of charm production in deep inelastic electron scattering yields 0.3% IC probability in the proton. A recent reanalysis of the EMC charm production data was carried out by Harris, Smith, and Vogt [53]. Their improved analysis found that an IC component is still needed to fit the EMC data, with a value indicated for the proton of $(1.0 \pm 0.6)\%$. The most probable IC state occurs when the constituents have the smallest invariant mass. In the rest system, this happens when the constituents are relatively at rest. In a boosted frame, this configuration corresponds to all constituents having the same velocity and rapidity [54, 55]. When a IC state is freed in a hadronic collision, the charm quarks should have approximately the same velocity as the valence quarks. They can then easily coalesce into charmed hadrons [51, 56, 57, 58] and produce leading particle correlations at large X_f . The IC component in an incident Σ^+ or proton can then lead to large X_f P^0 production. One may expect that P^0 production will be predominantly central for reaction mechanisms other than IC. Intrinsic charm Pentaquark production, with its expected high X_f distribution, would therefore be especially attractive.

For E781 and CHARM2000 one can study the diffractive pair production reactions ([22], see also [26]) $\Sigma^- + N \rightarrow (P^- D^0) + N$ and $p + N \rightarrow (P^0 D_s^+) + N$ (or even the coherent reactions of these types on nuclei), with possible D^0 , D_s^+ tag or without such tag. For the diffractive pair production cross section, one can compare to the diffractive cross section for the reaction $p + N \rightarrow (\Lambda K^+) + N$ at 70 GeV, which is more than $1 \mu b$ after subtraction of isobar contributions [26]. The ratio of diffractive cross sections σ_d was estimated [26]:

$$\sigma_d(P^0 D_s^+)[600 GeV] / \sigma_d(\Lambda K^+)[70 GeV] \sim (m_s/m_c)^2 \cdot R \sim 2. \times 10^{-4}. \quad (12)$$

Here the reduction factor R that accounts for the fusion in the P of an extra

two quarks is $R=2.5 \times 10^{-3}$ from Eq. 6. The factor $(m_s/m_c)^2$ accounts for the relative probability to produce charmed quark versus strange quark pairs. From the ratio of constituent quark masses [59], $(m_s/m_c)^2 \sim 8. \times 10^{-2}$. In Eq. 12, we do not explicitly show a kinematic factor, since its value [1, 26] is close to unity for the reactions shown. This factor accounts for the energy and mass dependence of the cross sections, for diffractive-like production of different final state masses with different beam energies. The increased Pentaquark cross section expected from energy extrapolation is offset by a reduction for making the heavier mass Pentaquark final state. We then find:

$$\sigma_d(P^0 D_s^+)[600 GeV] \sim 1 \mu b \times 2. \times 10^{-4} \sim 0.2 nb. \quad (13)$$

We assume conservatively that $B_w=0.05$ for such diffractive production searches, although with the smaller backgrounds expected at high X_f , one could possibly search for all visible decays ($B_w=0.08$). From the projected Pentaquark charm sensitivity shown in Table 1 for E781 (and roughly ten times higher for CERN CHEOPS [32]), it may be possible to observe the diffractive production process of Pentaquarks at the level of several hundred events. Future experiments in the spirit of the CHARM2000 workshop, with higher charm sensitivity than E781, should have improved chances to observe Pentaquarks.

5. Heavy Baryons with Hidden Charm

In recent years, several candidates were reported for baryon states with unusual properties (narrow decay widths, large branching ratios for the decays with strange particles). There are candidates for cryptoexotic baryons with hidden strangeness $B_\phi = |qqqs\bar{s}\rangle$, where $q = u$ or d quarks (see [1, 15, 60] and references therein). Further searches for nonstrange and cryptoexotic baryons with hidden strangeness are planned at IHEP (70 GeV proton beam) with the SPHINX spectrometer [60], and in FNAL E781 [61]. Although the existence of such a B_ϕ baryon is not yet confirmed, this suggestion raise the question of the possible existence of heavy cryptoexotic baryons with hidden charm $B_\psi = |qqqc\bar{c}\rangle$. These exotic Pentaquark baryons can either be direct five-quark states or $\phi - N$ and $\Psi - N$ bound states (resonances). The latter may form at low relative velocities of the meson and baryon constituents,

because of the strong attractive QCD Van der Waals interaction [58]. The intrinsic charm which was discussed in Section 4.4 may also be relevant for the production of the B_ψ baryon. If $M(B_\psi) < M(\eta_c) + M(p) \simeq 3.9$ GeV, the B_ψ decays would be OZI suppressed and the width of this cryptoexotic baryon would be quite narrow. If $M(B_\psi) > 4.3$ GeV, there would be OZI allowed decays $B_\psi^+ \rightarrow p + J/\psi$; $\Lambda_C^+ + D^0$, etc. Because of a complicated internal color structure of this baryon (see Introduction), one can expect a narrow decay width (≤ 100 MeV).

To search for such B_ψ states, it was proposed [62] to use the diffractive production reaction $p + N \rightarrow B_\psi^+ + N$ with possible decays of B_ψ baryons $B_\psi^+ \rightarrow p + (J/\psi)_{virt} \rightarrow p + (l^+l^-)$ or $B_\psi \rightarrow p + (\eta_c)_{virt} \rightarrow p + (K^+K^-\pi^+\pi^-; 2\pi^+2\pi^-; K\bar{K}\pi; \eta\pi\pi)$. For these processes, $\sigma B\epsilon$ was estimated as 0.2 - 0.5 nb/N [62]. For an appropriately designed experiment, with a charm sensitivity close to 10^4 events/(nb/N) of effective cross section, it should be possible to observe several thousand such events.

6. Conclusions

We described the expected properties of Pentaquarks. Possibilities for enhancing the signal over background in Pentaquark searches were investigated. General model-independent predictions were presented as well as those from two models: a loosely bound $D_s^- N$ “deuteron” and a strongly-bound five-quark model. While the current E791 may have marginal sensitivity, future experiments with more than 10^6 reconstructed charmed baryon events should have enough sensitivity to determine whether or not the Pentaquark exists.

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Table 1: Projected Pentaquark Yields

Model for estimation of $\sigma_{\Sigma^-}(P^0)$ at $P_{\Sigma^-} = 650$ GeV		$\sigma(P^0)/\sigma(D_s^-) \simeq 10^{-2} - 10^{-3}$ $\sigma_{\Sigma^-}(D_s^-) \simeq 5 \mu b/N$ FNAL E781
P^0 quasi- stable; $X_f > 0$	$\sigma_{\Sigma^-}(P^0) _{X_f > 0}$	$\sim 50 - 5 \text{ nb}/N$
	B_w	0.05
	ε_1	< 0.08
	$\sigma(P^0)_{\text{eff}}$	$< 0.2 - 0.02 \text{ nb}/N$
	N_w	$< 2800 - 280 \text{ events}$
P^0 $X_f > 0.5$	$\sigma_{\Sigma^-}(P^0) _{X_f > 0.5}$	$\sim 1.5 - 0.15 \text{ nb}/N$
	$B_s \text{ or } B_w$	0.05
	ε_2	< 0.25
	$\sigma(P^0)_{\text{eff}}$	$< 0.02 - 0.002 \text{ nb}/N$
	$N_s \text{ or } N_w$	$< 280-28 \text{ events}$

Notes to Table 1:

- Here $\sigma_{\Sigma^-}(P^0) = \sigma(\Sigma^- + N \rightarrow P^0 + X)$, etc. B_w is the effective branching ratio for visible weak decays of quasistable exotic Pentaquark baryons:
 $B_w = B[P^0 \rightarrow p\phi\pi^- + p\phi\pi^-\pi^+\pi^- + pK^{0*}K^-] \simeq 0.05$, as described in the text.
 B_s is the effective branching ratio for visible decays of a Pentaquark exotic baryon resonance:
 $B_s = B[P^0 \rightarrow pD_s^-] \cdot B[D_s^- \text{ visible}] \simeq (1.0) \cdot (0.05) \simeq 0.05$.
 $\sigma(P^0)_{\text{eff}} = \sigma_{\Sigma^-}(P^0) \cdot B \cdot \varepsilon$, where B is either B_w or B_s . We use $\varepsilon_1 < 0.08$ for the average efficiency for the reconstructed charm events in E781 for $X_f > 0$; $\varepsilon_1 < (\text{trigger efficiency}) \cdot (\text{reconstruction efficiency}) < (0.18) \cdot (0.45) = 0.08$ [29]. The efficiency depends on the lifetime, and also on the particular decay mode observed, and also on the average X_f value for Pentaquark events. We use $\varepsilon_2 < (0.55) \cdot (0.45) = 0.25$ for the same efficiency in the fragmentation region ($X_f > 0.5$); since the trigger efficiency is higher [29] for higher X_f particles. We estimate the Pentaquark production cross section in the fragmentation region (quasi-stable or resonant) as $\sigma_d \sim 0.03 \cdot \sigma(X_f > 0)$. N_w is the number of weak decay events for quasistable P^0 . N_s is the number of decay events for a resonance P^0 . The estimated events are extrapolations for a planned Fermilab E781 1996-97 50 week data run [29]: 1.3×10^{11} interactions in the target, an estimated 2.8×10^8 charm events, and a sensitivity of roughly $1.4 \times 10^4 \text{ events}/(\text{nb}/N)$ of effective charm cross section. The values cited for N_w and N_s are only projected upper limits, as described in the text.

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